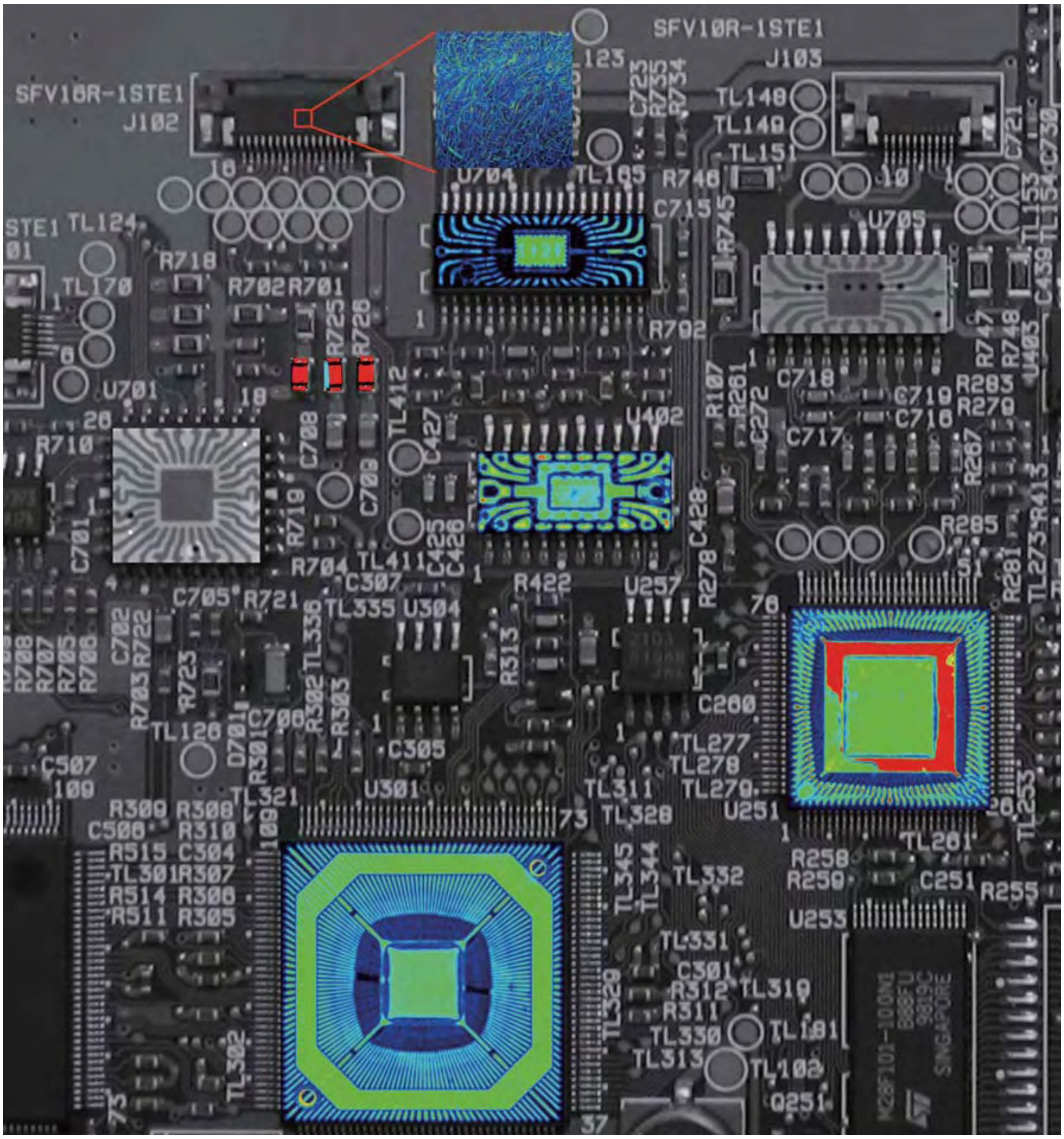
Technical data

What can be achieved?

Scanning Acoustic Tomograph



Hitachi Kenki FineTech Co., Ltd.

http://www.hkft.co.jp

Contents

What is Ultrasound?

Ultrasound is not audible to the human.

A sound wave can be produced by vibrating or shaking a material back and forth, and the wave travels from one place to other in a medium. If the material is shaking faster, the higher pitch sounds are generated, and slower vibration produces lower pitch sound waves. The frequency, or number of vibration cycles in a second, is measured by a unit Hertz (Hz), and human ear is audible to the sound frequencies from 20 to 20,000Hertz (Hz). The inaudible frequency range over 20,000Hertz is called as the ultrasound region.

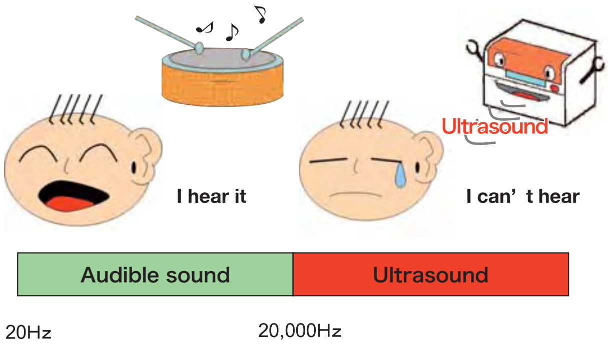


Figure 1: Audible sound and ultrasound

In modern technology, ultrasound has long list of applications in the high-tech industry and in the medical field, in order to visualize the internal structures, as well as finding flaws, measuring distances, optimizing the process, and cleaning materials, etc.

Characteristics of Ultrasound

Ultrasound has the following properties:

① For traveling or propagation of acoustic waves, a medium is essential. Ultrasound will only travel in a molecular medium, e.g., air, gas, liquids, and solids.

② Ultrasound will reflect and or penetrate when it encountered to a boundary shared by two different mediums. The amount of energy portions reflected and transmitted at the boundary interface depends on the types of mediums sharing the boundary.

③ Propagation speed in a medium depends on the constituent molecules of the medium. Since ultrasound beam travels at lower speed compared to light rays or X-rays, it is possible to measure the time required for its travel across a smaller distance.

④ The ultrasound beam travels straighter ahead at a higher frequency, while a lower frequency beam penetrates deeper due to lesser energy loss or lesser attenuation.

Because of the ultrasound property ①, it is applicable to detect the flaws hidden inside a structure by acquiring ultrasound images. Property ② allows us to detect small air voids enclosed in a solid or delamination between the bonded materials. Property ③ makes it possible to accurately measure material thickness in particular structure and locating depths where the flaws exist. Property ④ stipulates that the choice of ultrasound frequency is depended on the intended application or purpose.

As the typical energy of ultrasound beam used in an imaging equipment is lower than 0.1mW/cm^2, it is neither destructive to any material samples, nor harm to the human body.

❐ Application Examples for Target Finding and Flaw Detection

Figure 2 shows some examples of ultrasound applications in target finding and flaw detection. Appropriate frequency range essentially depends on the target sample type and detection objective. Ultrasound imaging systems typically use at sound frequency ranging from 1 to 300MHz to inspect today's sophisticated samples structured with metals, semiconductors, ceramics, and epoxy or resins, etc.

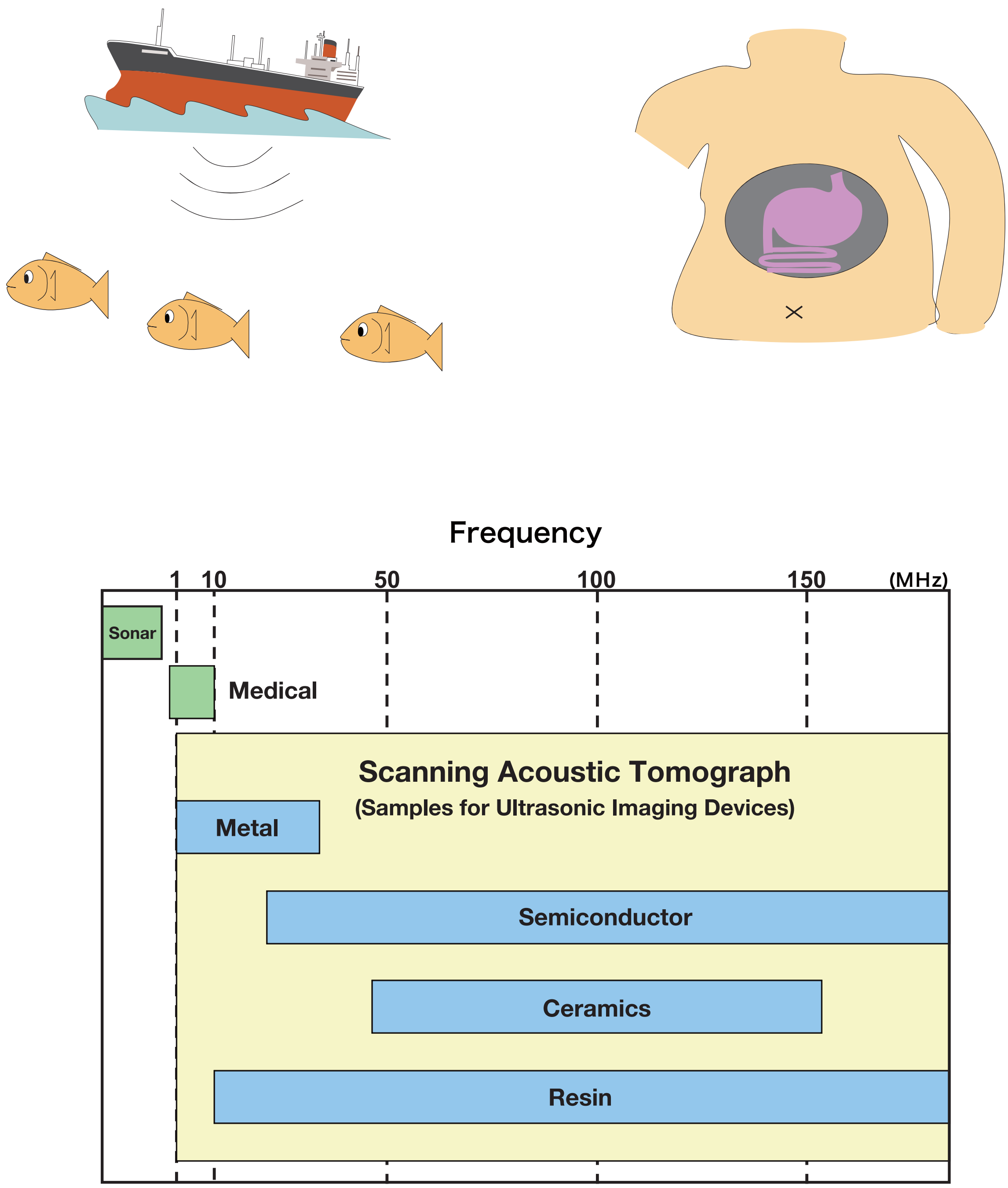
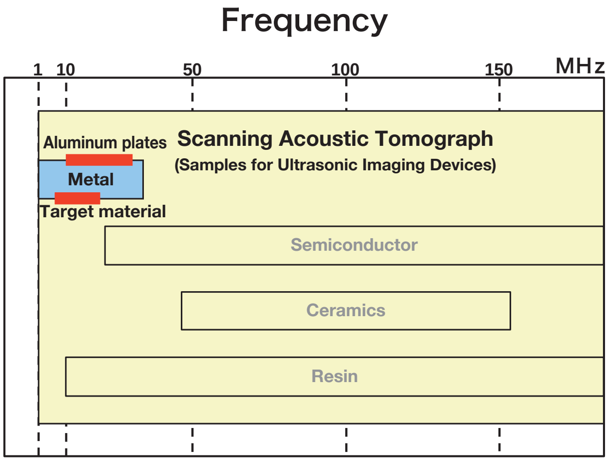
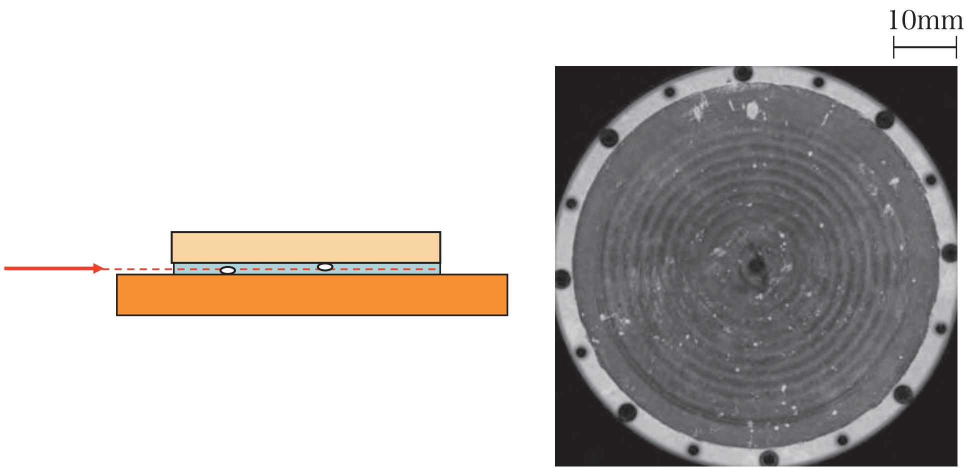


Figure 2: Application examples of ultrasound waves

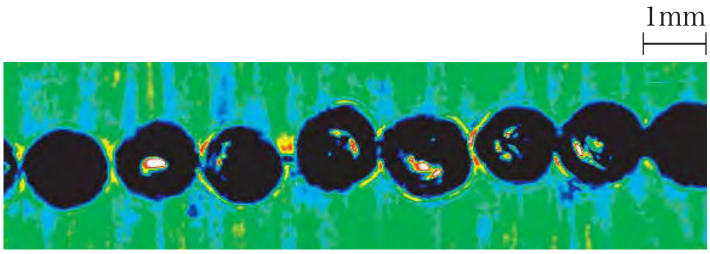


<Metals>

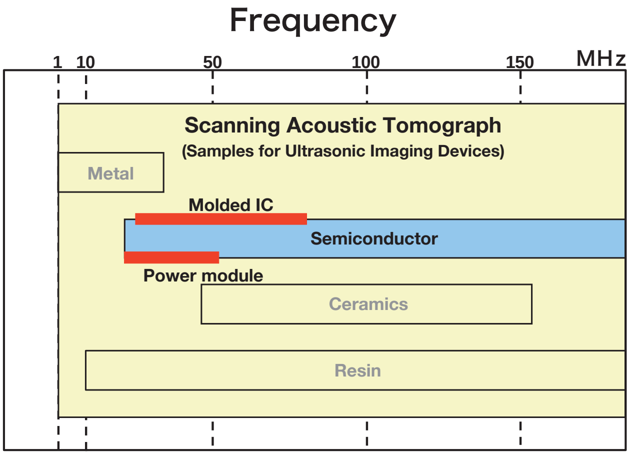
To inspect the metal structures, ultrasound is extensively used for finding voids at the interface of spattering target material jointed with a backing plate. It is also applied in detecting the voids at the welded aluminum plates, as well as finding voids enclosed in the metal blocks.



Spattering target material (Interface)



Spot welded joints of aluminum slabs



<Semiconductors>

Semiconductor packaging technology has developed various types of packages and structures. Conventionally, ultrasound images are routinely used in defect detection of molded ICs, especially to inspect resin / die / leadframe individual interface qualities and resin voids. In recent years, the requirements for automotive electronic device inspections, such as thorough inspection of voids at heat-sink/ substrate interface of power modules utilized in hybrid cars, have increased.

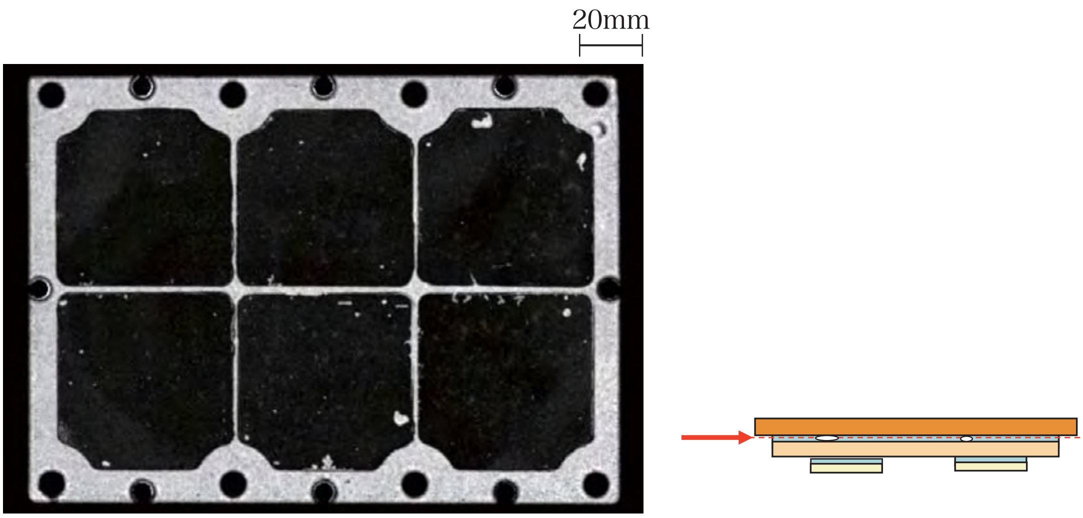
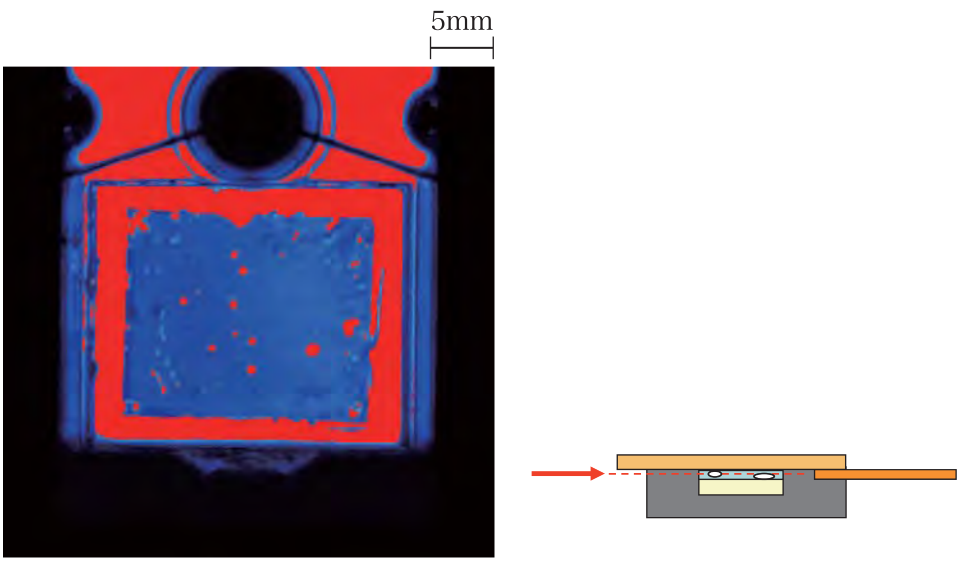
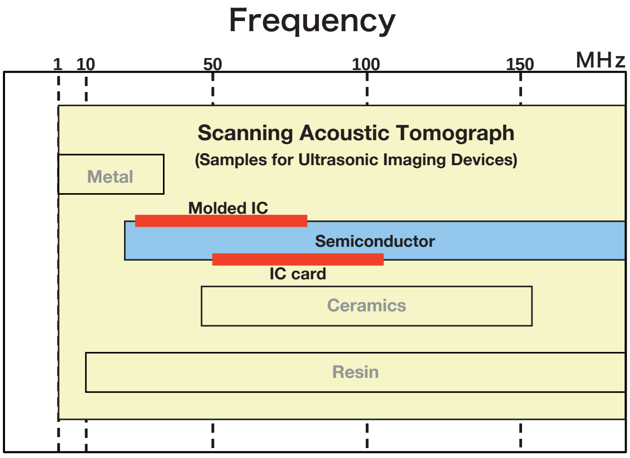


Image of automotive power module device (Heat-sink / Substrate interface)



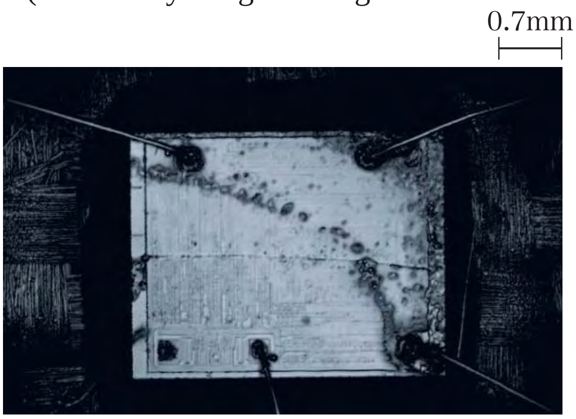
Automotive Power Transistor (Chip / Heat-sink interface)



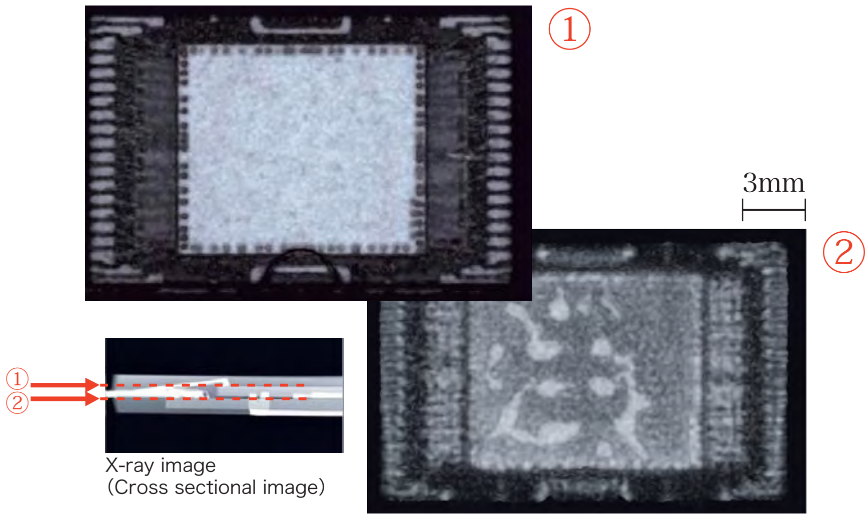
<Semiconductors>

With Ultrasonic Imaging Devices (Scanning Acoustic Tomograph™) it is possible to detect cracks in thin chips which are hard to see with X-ray imaging technique. In addition, recent demand to catch delaminations at individual chip interfaces in a multi-chip stacked structure has increased.

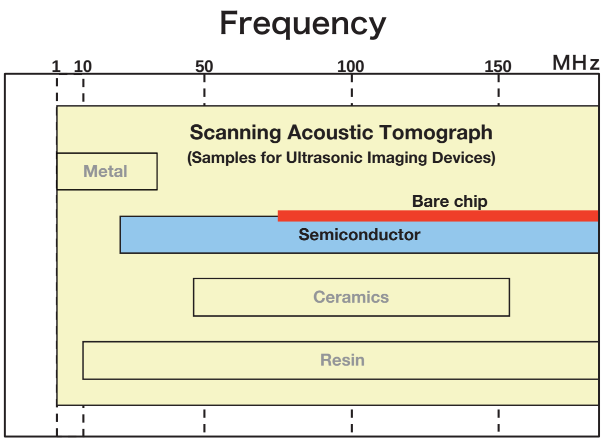
IC card (Left: X-ray image Right: Ultrasonic image)



Chip surface cracks

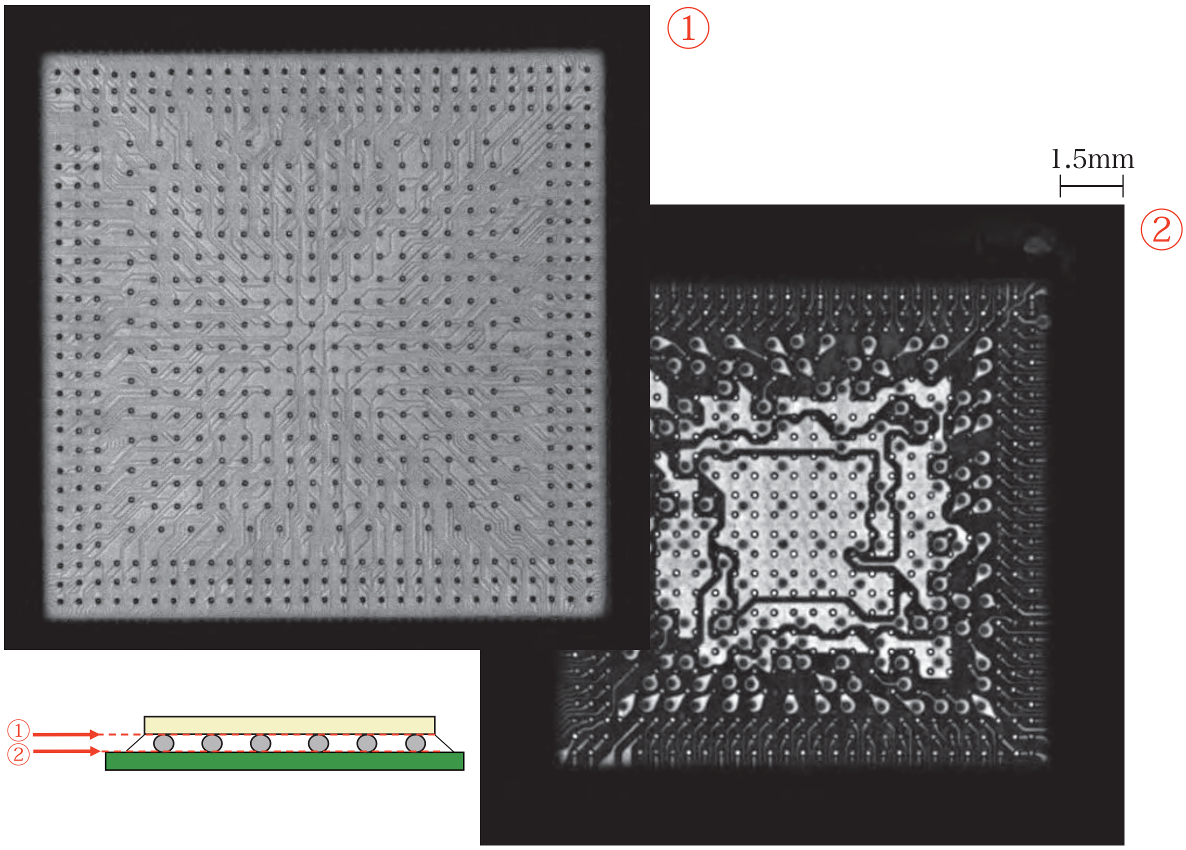


Stacked IC (① Resin / Chip and ② Chip / Chip interface)

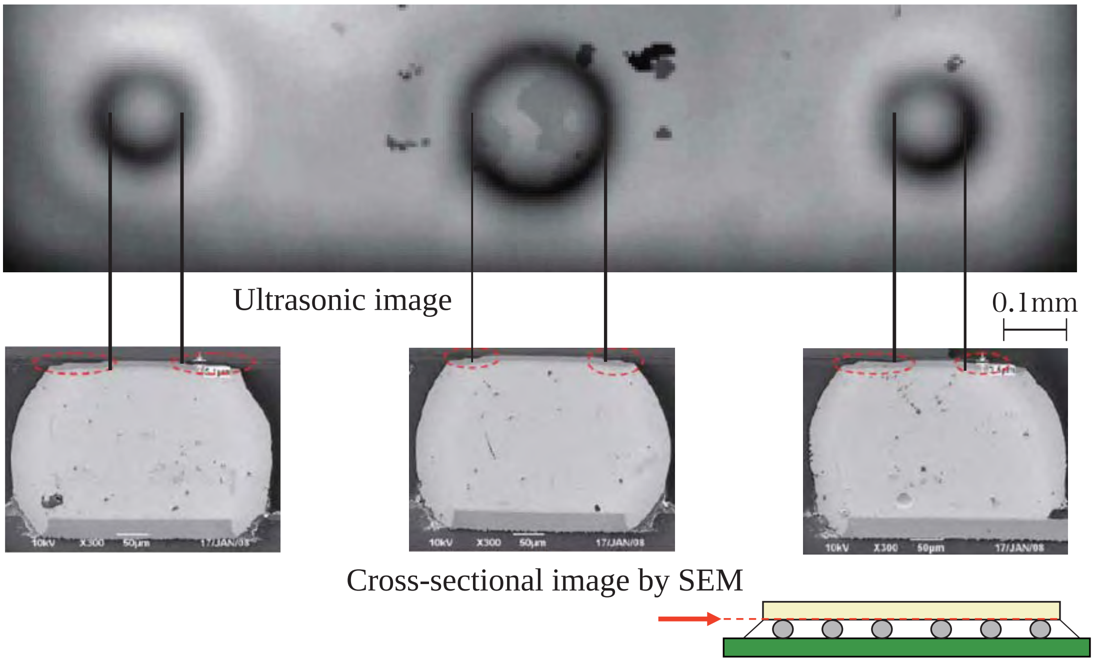


<Semiconductors>

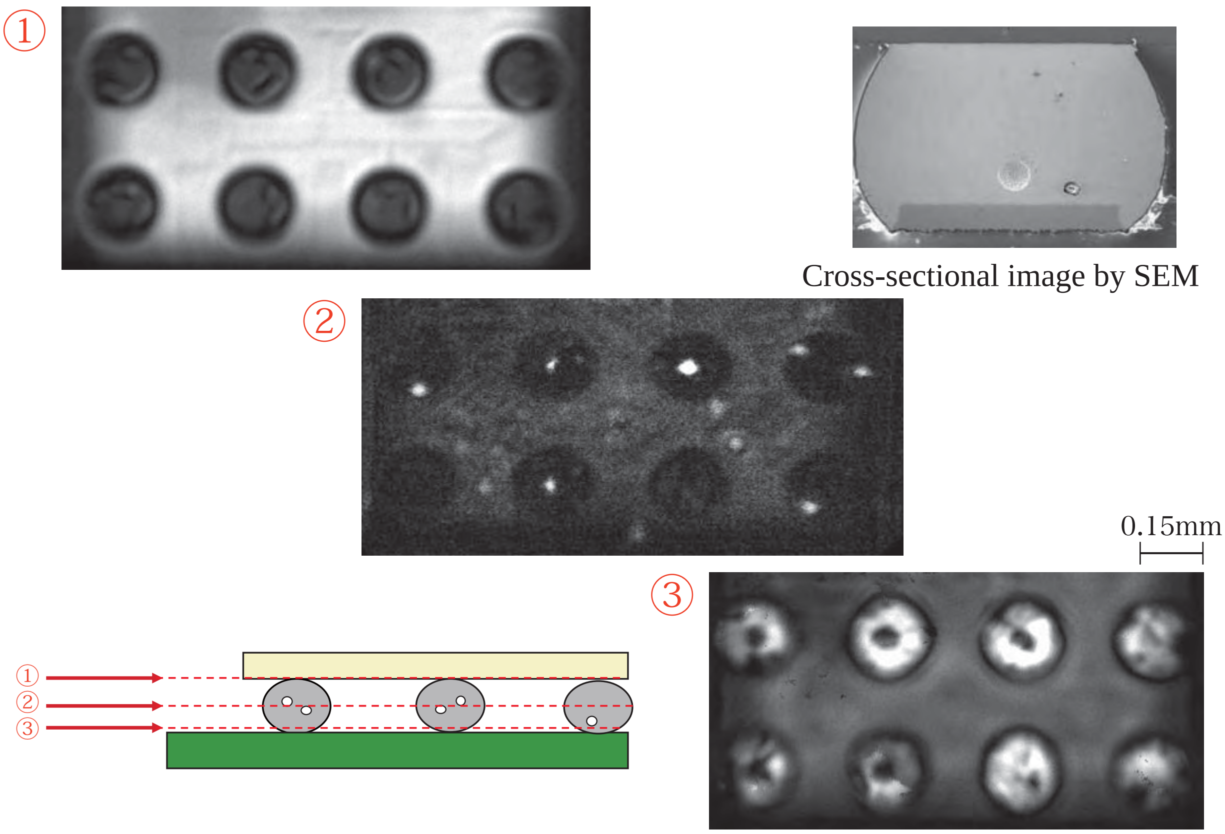
For flip chip package inspection, ultrasound waves at higher frequencies are particularly useful to image the delamination between the chip and underfill, voids inside underfill material, and solder bump welding conditions.



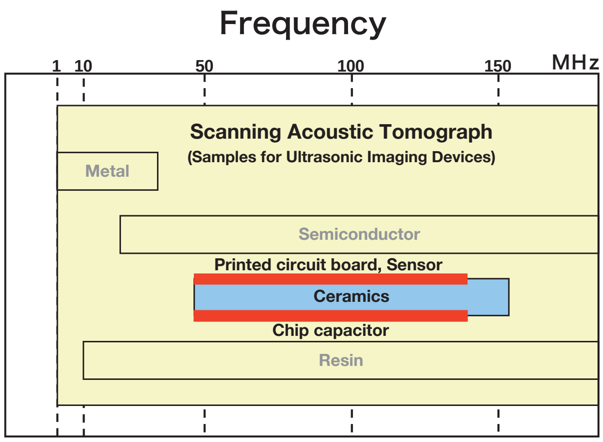
Bare chip (①Chip / Underfill interface, and ②Underfill / Substrate interface)



Bare chip (Chip / Solder Bump interface)

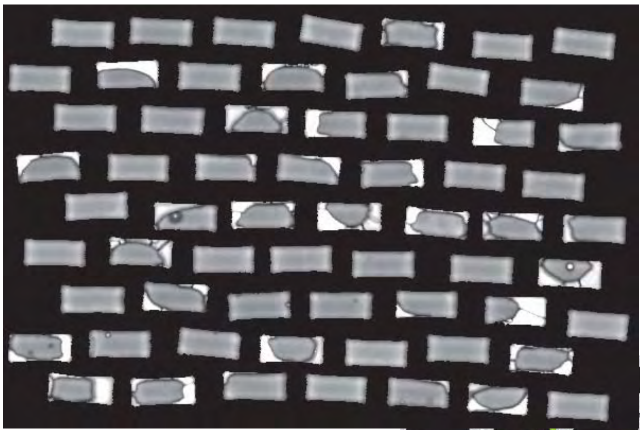


Bare chip (Voids in Solder Bumps)

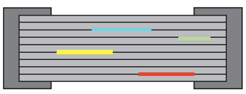


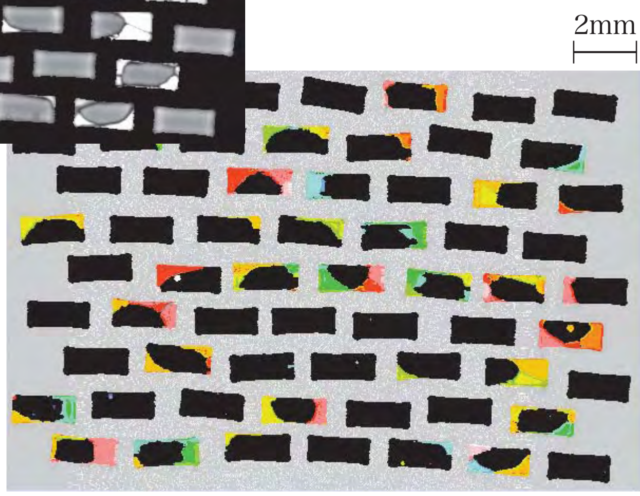
<Ceramics>

As for the ultrasound applications in engineering ceramics, layer crack detection of multi-layered ceramic capacitors (MLCC), sensors, as well as the printed circuit boards are some examples.



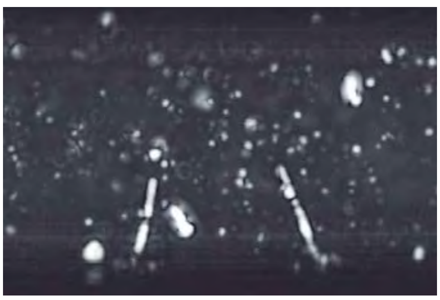
Reflection image of MLCC





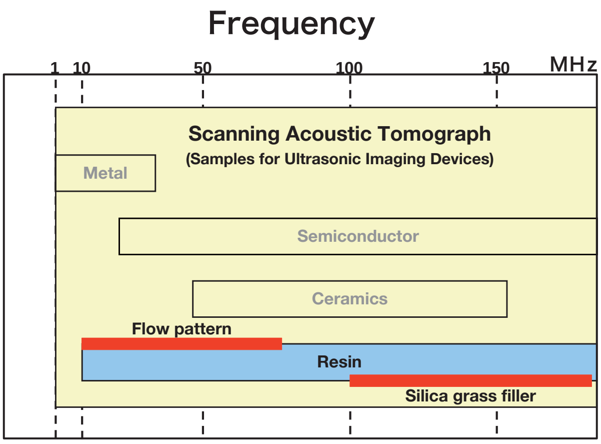
Time-of-Flight image of MLCC

Multi-layered ceramics capacitors (cracks in electrode layers)



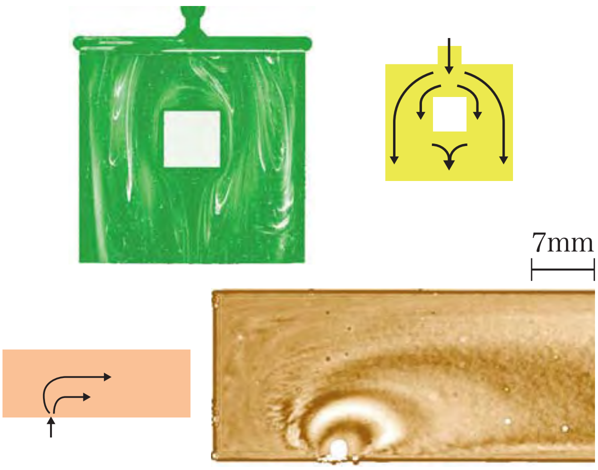
φ40μm φ50μm

Ceramics image revealing defects created by buried wires

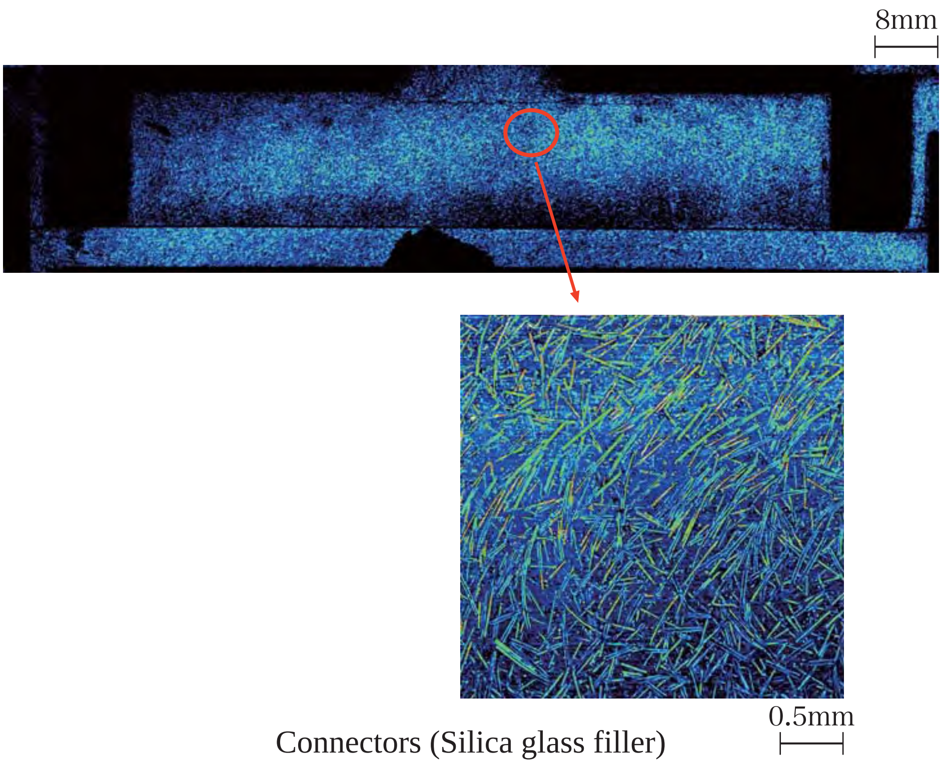


<Resins>

There also is wide range of applications in resin inspection, including welding conditions, voids inside resin, ability to image flow patterns of injected resin, as well as silica filler richness.



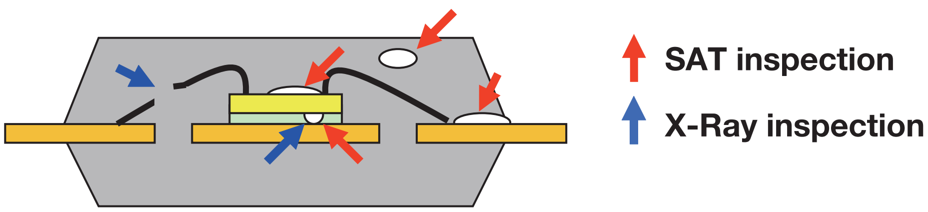
Resin flow pattern

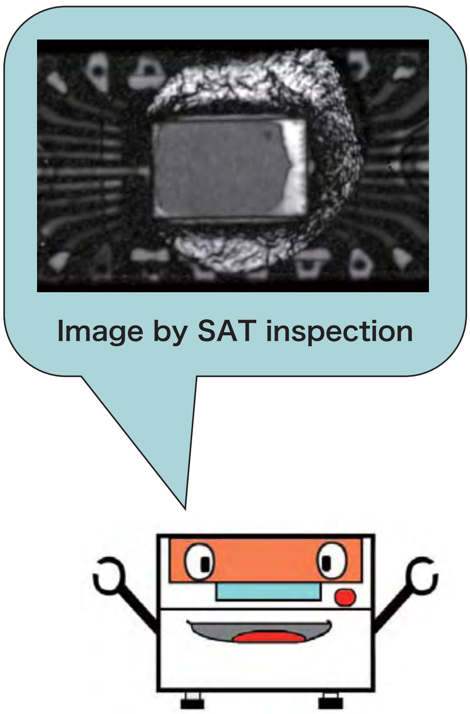


Connectors (Silica glass filler)

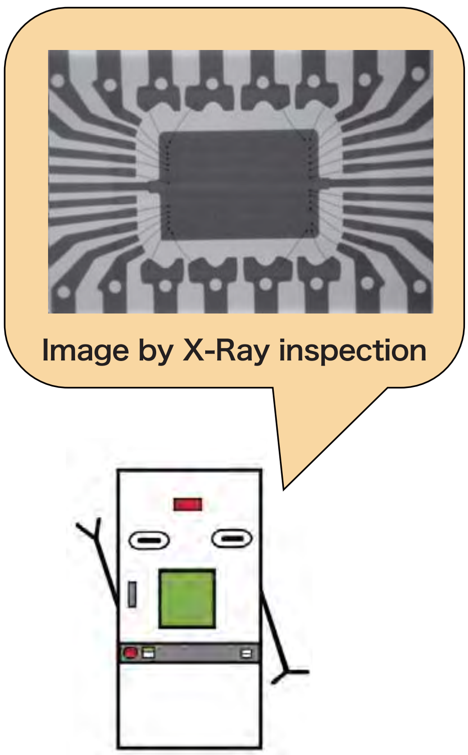
❐ Notes on X-Ray and SAT Inspection Techniques

For non-destructive inspection and analysis purposes, Scanning Acoustic Tomograph™ (SAT) and X-Ray imaging systems are most commonly employed tools. The information extractable from the images acquired by these tools is also quite different.
Inspection of encapsulated IC packages, for instance, the x-ray system is very efficient in imaging bonding wires sways as well as detecting voids inside solder bumps. Compared to ultrasound, x-ray has superior capability in projecting at arbitrary sample orientation and viewable for any sample shapes. Generally speaking, however, x-ray imaging required to have an intensity difference at least 3% of total penetrated thickness. This severely limits the x-ray technique for detecting small planar gaps like delamination perpendicular to the direction of x-ray propagation.
Although both SAT and X-Ray imaging methods have advantages and disadvantages, they compliment each other in finding minute defects enclosed in the package structures.





Scanning Acoustic Tomograph model
character: Little Brother SAT



X-Ray Inspection System model
character: Brother MF

❒ Scanning Acoustic Tomograph

The Ultrasonic Imaging Device to be introduced in detail here is called Scanning Acoustic Tomograph (SAT), a high resolution imaging tool, designed, manufactured, and distributed worldwide by Hitachi Kenki FineTech Co., Ltd.

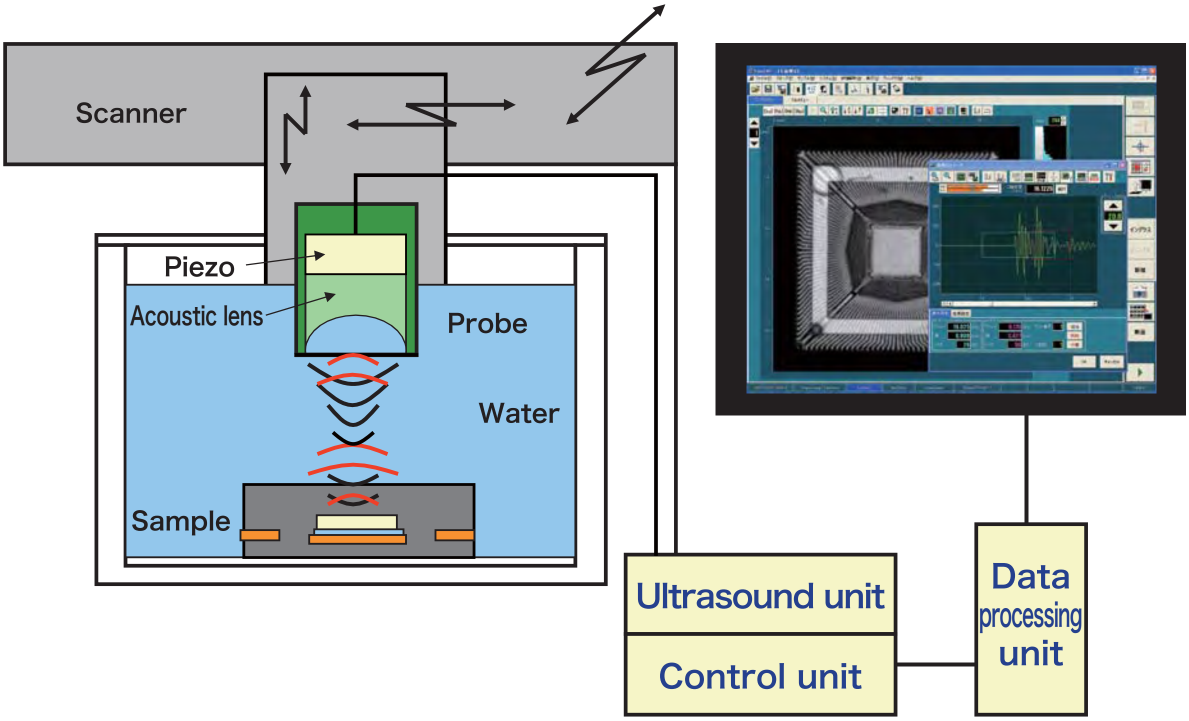


Figure 3: Functional Structure of a Scanning Acoustic Tomograph.

To create an image, let us apply the characteristic property of ultrasound that a portion its energy will reflect when it encountered a boundary formed by a material dissimilar to currently traveling material. The ultrasound is generated by applying pulsed voltage to a piezo crystal in the probe attached on a 3-axis scanner mechanism. The sound wave is focused by an acoustic lens to form a beam and it is impinged into a sample.

The echoes reflected back from inside out of the sample are collected by the same probe to amplify and digitally process for image construction. The resultant image is displayed on a PC monitor, brighter contrast for stronger reflection regions and darker for weaker reflections. By scanning probe across the area of interest, gray scale acoustic images are acquired to represent internal structure of the sample.

The intensity of reflected acoustic wave depended on the property difference between the impinging and reflecting materials which have different acoustical impedances. The echo intensity is stronger if the impedance difference is larger. In addition, the traveling speed of ultrasound is relatively slow so that the echo arrival times are spreading along the time axis enabling one to identify and pick the echo originated from a certain depth of interest within a precisely gated time window. The echo intensity and wavelength depend on material properties. With these advanced functions, SAT system provides qualitative and quantitative information from the interface of interest including existence of voids, cracks, and delamination, etc.

Table 1: Sound velocity, Wavelength, Acoustical impedance and Reflectivity

Material	Sound velocity (Longitudinal wave) m/s	Wavelength (25MHz) mm	Acoustic impedance $10 kg/m^2 s$	Reflectivity %			
				Silicon	Metal	Resin	Water
Air	344	0.01	0.0	100	100	100	100
Water	1480	0.03	1.5	86	93	64	
Resin	3930	0.16	6.8	50	74		
Metal	5900	0.24	45.4	39			
Silicon	8600	0.34	20				

Sound velocity (Longitudinal wave): $C = \sqrt{\dfrac{E(1-\sigma)}{\rho(1+\sigma)\cdot(1-2\sigma)}}$ (m/s)

Wavelength: $\lambda = C/f$ (mm)

Acoustic impedance: $Z = \rho \cdot C$

Reflectivity: $R = (Z_2 - Z_1)/(Z_2 + Z_1)$

Where E : Young's Modulus, σ : Poisson's Ratio, ρ : Density, f : Frequency,
Z_1 : Acoustic impedance of incidence side material
Z_2 : Acoustic impedance of reflecting side material

Scanning Acoustic Tomograph FineSAT (Type II)

❐ Images Acquired by Scanning Acoustic Tomograph System

C-Scope is one commonly referred imaging mode in using acoustic imaging systems, in which plane images are constructed from the echo peaks reflected from a boundary of interest usually enclosed in a package structure. Figure 4 shows such C-scope image data revealing the interior plane of a molded resin IC package. By inspecting this data, one can tell whether there exist undesirable voids, delamination at the resin to chip or lead frame joints, resin cracks, and chip cracks.
Additionally, the images by other acquisition modes are shown in Figure 5 to 13.

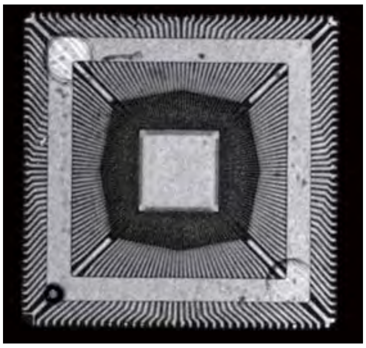


Figure 4: C-Scope image of an IC package

Figure 5: A-Scope data

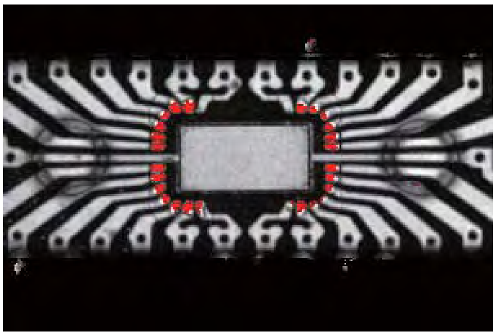


Figure 6: Polarity comparison mode image
(Selectively color-emphasizing the delaminated area)

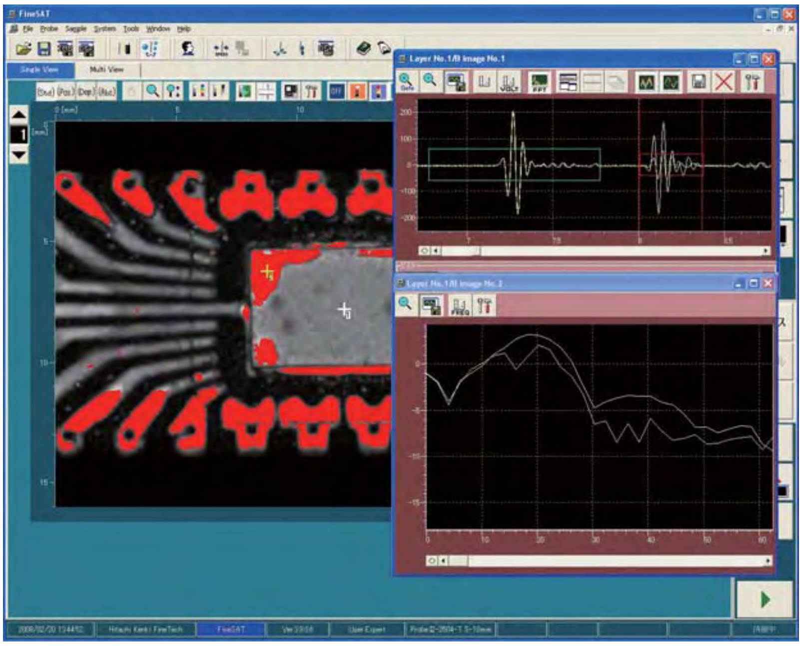


Figure 7: FFT processing

The A-Scope mode shown in Figure 5 is not only very useful for adjusting focus point, determining the depth of interest or gate width and height settings, but also measuring sound velocity and distances, quick confirmation of echo characteristics on each point of interest including intensities and phases that appears to reverse when ultrasound wave impinged from higher to lower impedance material. In Figure 6, we use the polarity inversion characteristics to emphasize delaminated region coded by colors: this mode of imaging is also known as Polarity Comparison Mode (PCM) as patented by Hitachi. Moreover, the same A-scope data can also be processed by using FFT frequency domain analysis as shown in Figure 7, to reveal the difference in number of peaks associated to the echoes of different sites.

Figure 8 shows a B-scope or cross-sectional image data, with which resin crack advancing directions and depth locations of voids can be inspected.

Figure 9 is created from depth profile data by color-coding of different depths. Figure 10 show the reflection and transmission images of multi-layer BGA package. The S-image shown in Figure 11 is another innovation by Hitachi to first image a sample diagonally so that target depth can be quickly focused by a mouse click and other measurement parameters can also be easily optimized.

Figure 12 is called Lamino image where individual layers of different depths can be imaged by a single pass.

Figure 13 shows the 3D image obtained by volumetric scanning that acquires all the waveform data from all points.

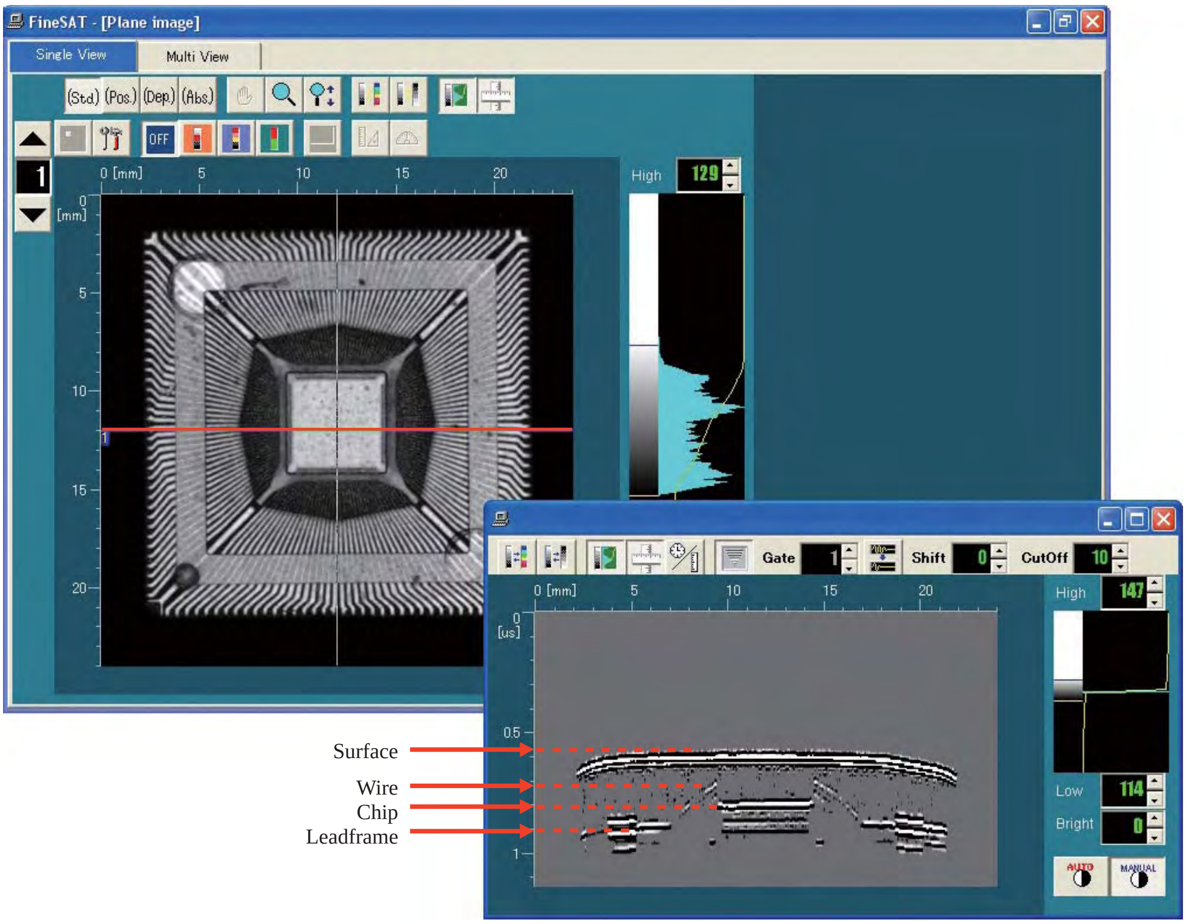
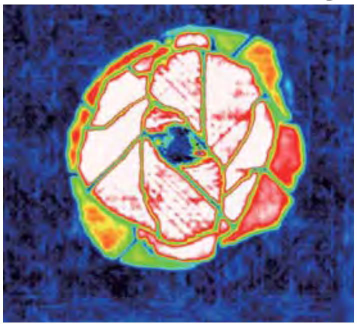
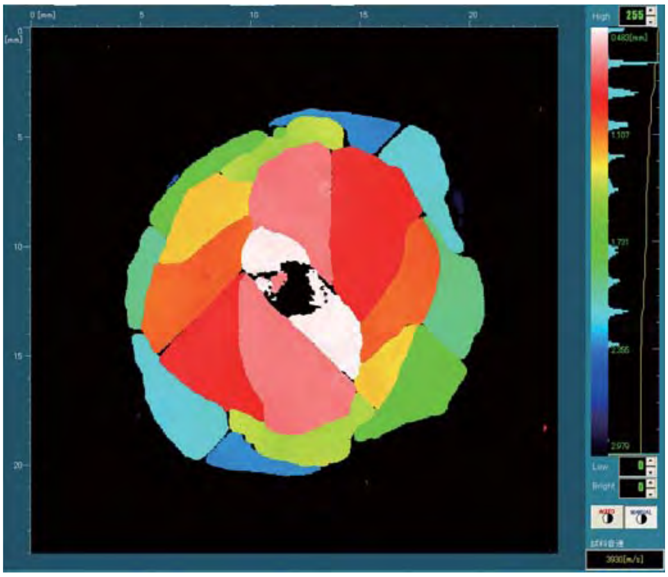


Figure 8: B-scope image (Cross sectional image)

Reflection image



Depth profile or Time-of-Flight image



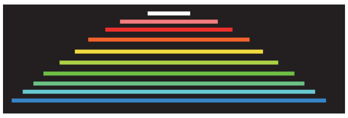
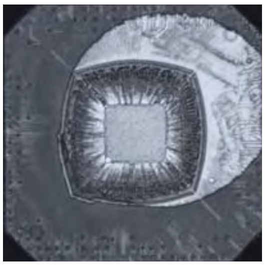
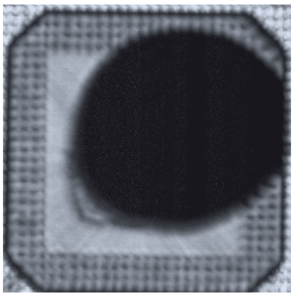
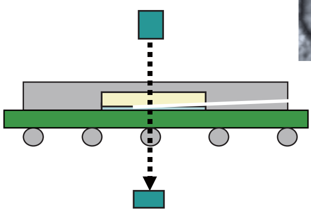


Figure 9: Depth profile or Time-of-Flight image
(Color-coded depth profile of delamination inside a CFRP sample)



Reflection image





Through Transmission image

Figure 10: Through Transmission image
(BGA)

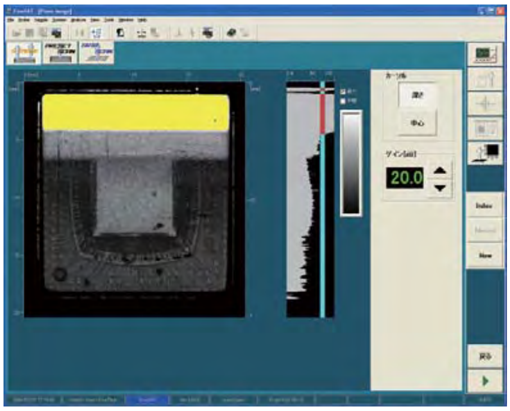


Figure 11: S-image
(Slanted imaging by diagonal cross-sectional scanning)

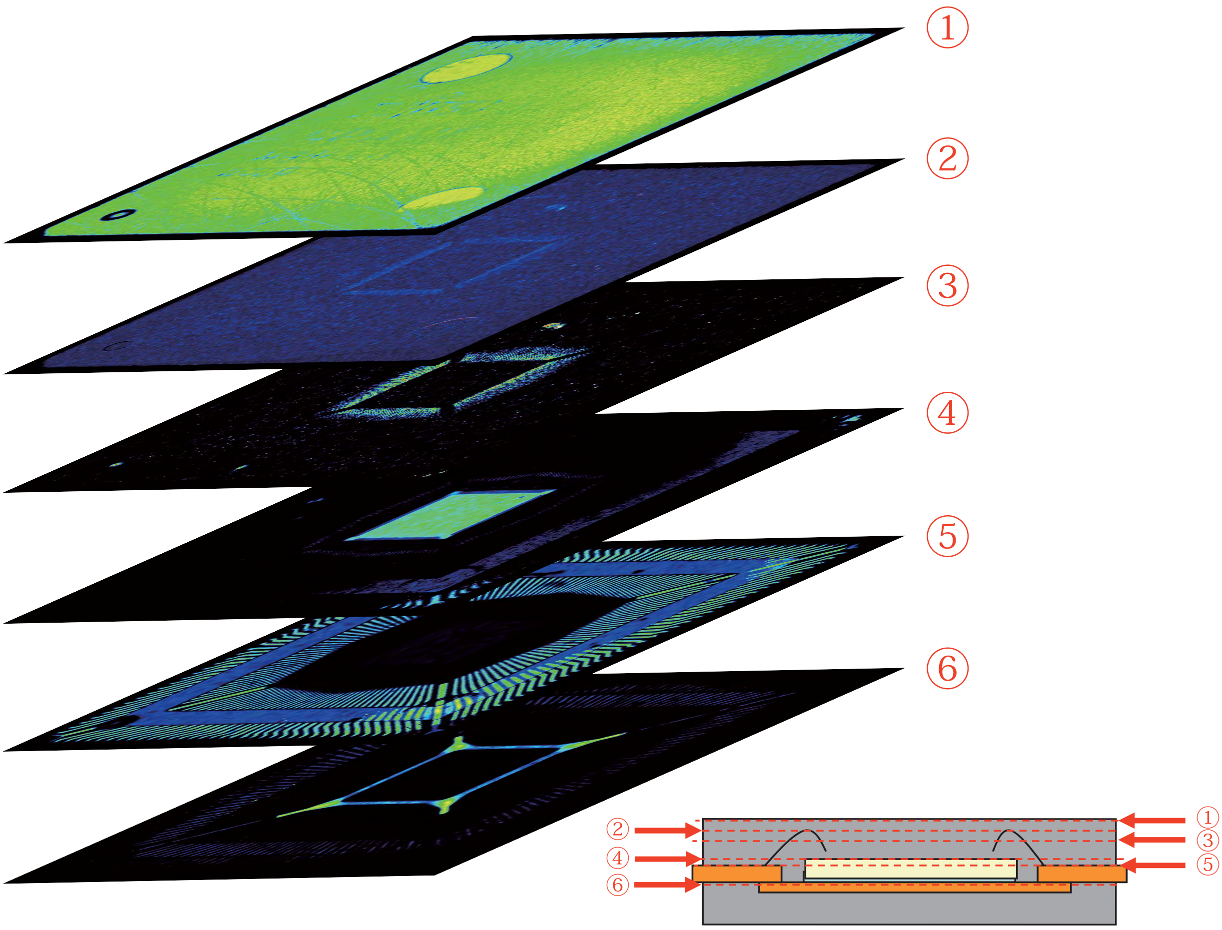


Figure 12: Images at different depths of an IC Package

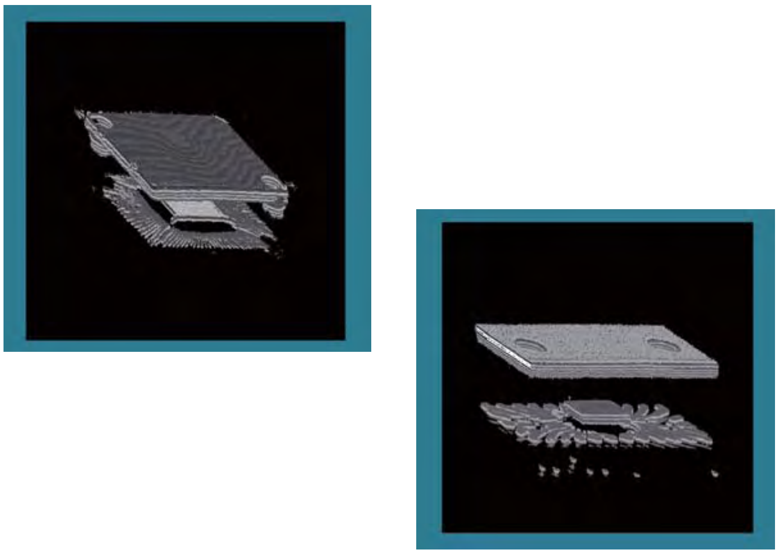


Figure 13: 3D Image of an IC Package

As volumetric scan mode stores all waveform shapes in a 3D data file, the waveform at any point can later be retrieved and analyzed. Images can be reconstructed after adjusting gate settings as desired, or image construction by using only a particular frequency. Moreover, the data can be processed to obtain intensity and or depth profile images, bitonal processing to estimate flaw area contribution in a predefined image area.

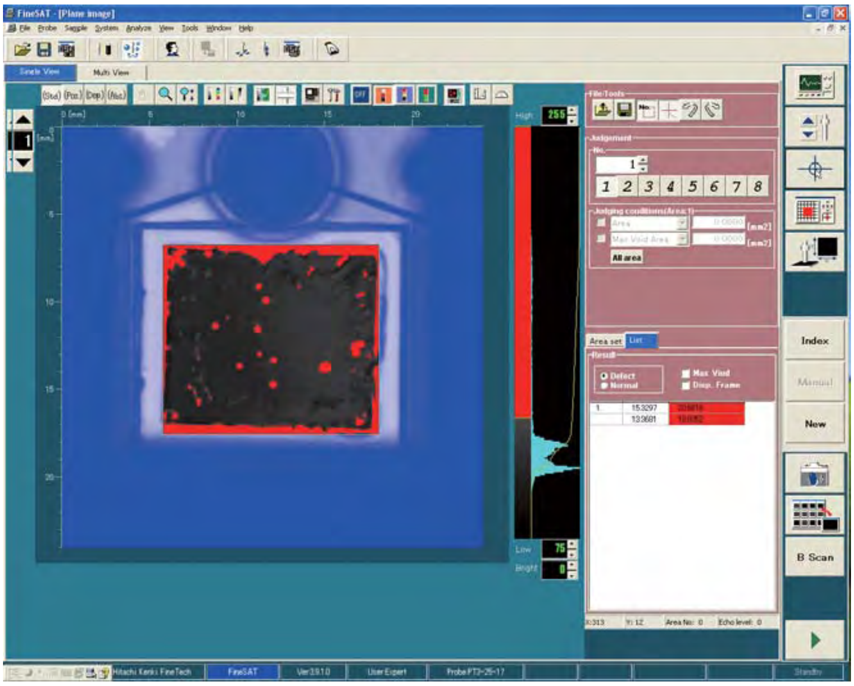


Figure 14: Evaluating ratio of flaw area to user defined area
(Void area, Maximum void area ratios)

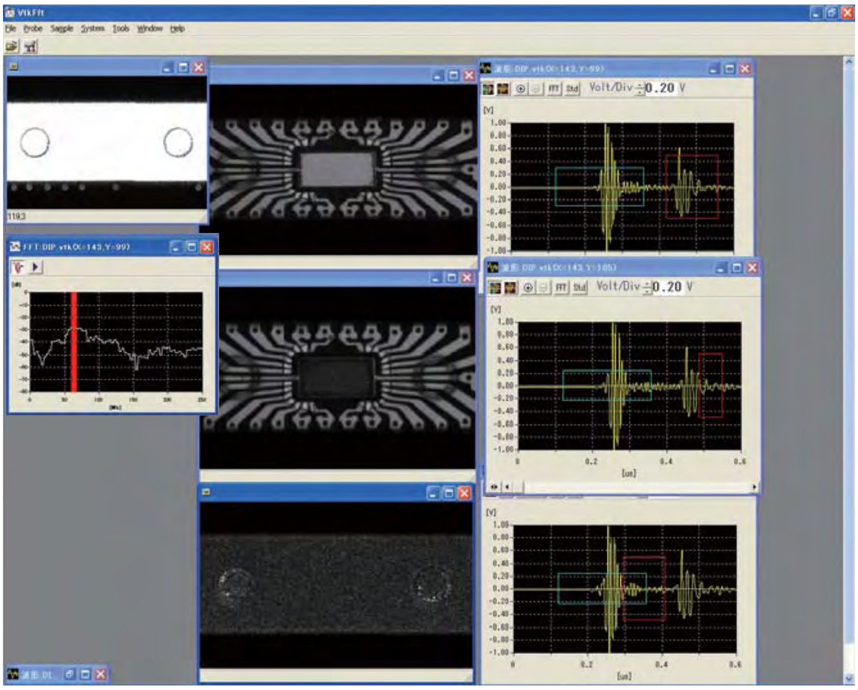


Figure 15: Processing data from Volume scan data. Display the waveform of desired area, Fast Fourier Transform (FFT) and image construction, gate settings and image construction.

Detectability and Resolution

The detectability and resolution of a Scanning Acoustic Tomograph system depends on:

- Probe frequency, focal length, damping characteristics
- Bandwidth of ultrasonic flaw detection system, linearity in signal amplification electronics
- Accuracy and Precision of positioning scanner
- Measurement conditions
- Sample shape and material type

With profound knowledge and experiences in ultrasound detection technology for over 20 years, Hitachi Kenki FineTech company have been providing with higher performance probes, better flaw detectors, precise scanner mechanisms, and user friendly software controls and analytical tools. As a result, our products have advanced to detect a 1µm created defect as shown in Figure16. Furthermore, independent of probe frequencies, 5nm delamination gaps can easily be detected.
A pair of 525µm thick, carefully patterned silicon wafers are fused to form nm cavities encapsulated by silicon material. Various probes with frequencies from 15-100MHz were utilized to inspect the silicon sample. Figure 17 shows an acquired image form this sample confirming that 5nm height gaps are detectable with Hitachi probes at any frequency covered by the range.

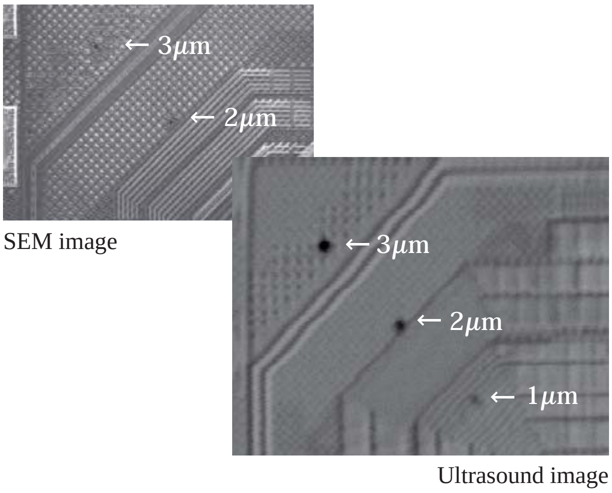


Figure 16: Imaging the flaws sizes 1µm, 2µm, 3µm diameter

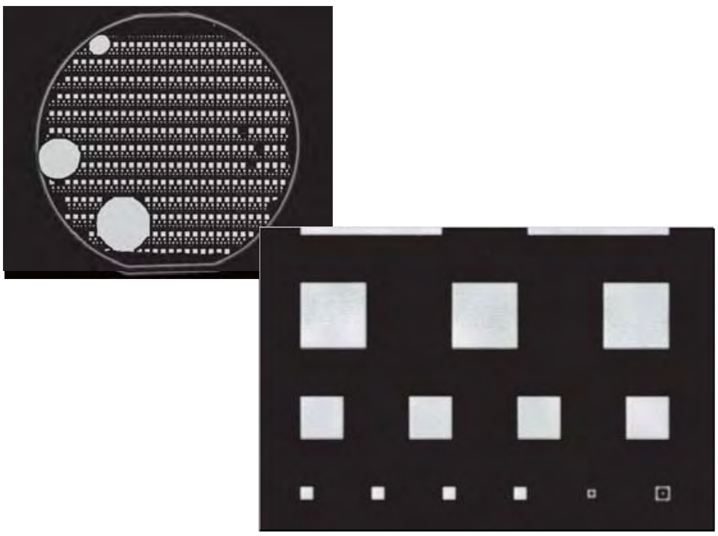


Figure 17: Fused interface of silicon wafers with 5nm height patterns

Quick Guide Table for Sound Velocity

t=CT/2

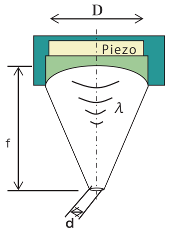
T=2t/C=2t(mm) /C(km/sec) (μsec)

Distance travelled in 50nsec

t = Thickness(mm)
T = Time(μsec)
C = Sound velocity (km/sec)

	Sound velocity (longitudinal waves) (m/s)	Verocity ratio	Wavelength at 25MHz (μm)	Travel time to 1mm distance (nsec)	Distance travelled in 50nsec (μm)	Density (10kg/m)	Acoustic impedance (10kg/ms)
Air (20℃)	344	0.2	13.8	5814	8.6	0.001	0.00
Water (20℃)	1480	1.0	59.2	1351	37.0	1.00	1.5
Polyethylene	1900	1.3	76.0	1053	47.5	0.92	1.7
Solder	1980	1.3	79.2	1010	49.5	12.60	24.9
Antimony Sb	2160	1.5	86.4	926	54.0	3.80	8.2
Lead Pb	2170	1.5	86.8	922	54.3	11.40	24.7
Vinyl chloride	2300	1.6	92.0	870	57.5	1.44	3.3
Rubber (hard)	2300	1.6	92.0	870	57.5	1.20	2.8
Polystyrol	2340	1.6	93.6	855	58.5	1.05	2.5
Molybdenum Mo	2350	1.6	94.0	851	58.8	1.70	4.0
Polymid	2460	1.7	98.4	813	61.5	1.06	2.6
Bakelite	2590	1.8	103.6	772	64.8	1.40	3.6
Epoxy resin	2500～2800	1.7～1.9	100～112	800～714	63～70	1.15～1.3	2.9～3.6
Acrylate resin	2720	1.8	108.8	735	68.0	1.18	3.2
Cadmium Cd	2780	1.9	111.2	719	69.5	8.60	23.9
Silver paste	2925	2.0	117.0	684	73.1	4.00	11.7
Tin Sn	3230	2.2	129.2	619	80.8	7.30	23.6
Gold Au	3240	2.2	129.6	617	81.0	19.30	62.5
Silver Ag	3600	2.4	144.0	556	90.0	10.50	37.8
Mold resin	3930	2.7	157.2	509	98.3	1.72	6.8
Platinum Pt	3960	2.7	158.4	505	99.0	21.40	84.7
Ice	3980	2.7	159.2	503	99.5	1.00	4.0
Zinc Zn	4170	2.8	166.8	480	104.3	7.10	29.6
Zirconium Zr	4650	3.1	186.0	430	116.3	6.44	29.9
Copper Cu	4700	3.2	188.0	426	117.5	8.90	41.8
German silver	4750	3.2	190.0	421	118.8	8.40	39.9
42Alloy	5020	3.4	200.8	398	125.5	8.15	40.9
Tungsten W	5460	3.7	218.4	366	136.5	19.10	104.3
Silica glass	5570	3.8	222.8	359	139.3	2.70	15.0
Nickel Ni	5630	3.8	225.2	355	140.8	8.80	49.5
Teflon	5710	3.9	228.4	350	142.8	1.35	7.7
Quartz	5750	3.9	230.0	348	143.8	2.65	15.2
Magnesium Mg	5770	3.9	230.8	347	144.3	10.00	57.7
Stainless steel(SUS304)	5790	3.9	231.6	345	144.8	7.91	45.8
Germanium Ge	5944	4.0	237.8	336	148.6	5.32	31.6
Steel	5870～5950	4.0	235～238	341～336	147～149	7.80	45.8～46.4
Iron Fe	5950	4.0	238.0	336	148.8	7.86	46.8
Stainless steel(SUS405)	5980	4.0	239.2	334	149.5	7.67	45.9
Silicon dioxide SiO_2	6000	4.1	240.0	333	150.0	2.20	13.2
Aluminum Al	6260	4.2	250.4	319	156.5	2.70	16.9
Zirconia ZrO_2	6994	4.7	279.8	286	174.9	5.90	41.3
Chrome Cr	7020	4.7	280.8	285	175.5	7.19	50.5
Sintered hard alloy	6800～7300	4.6～4.9	272～292	294～274	170～183	11～15	74.8～109.5
Titanium Ti	7300	4.9	292.0	274	182.5	3.00	21.9
Silicon Si	8600	5.8	344.0	233	215.0	2.33	20.0
Alumina Al_2O_3	10410	7.0	416.4	192	260.3	3.80	39.6
Silicon nitride Si_3N_4	10743	7.3	429.7	186	268.6	3.20	34.4
Silicon carbide SiC	12043	8.1	481.7	166	301.1	3.10	37.3
Berylium Be	12890	8.7	515.6	155	322.3	1.82	23.5

Estimation of ultrasonic beam diameter at focal point



Ultrasonic beam diameter at the focal point

$d = 0.71\lambda f/(d/2)$

λ:Wavelength
f:Focal length
D:Transducer Diameter

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